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CHALLENGES IN W-PAIR PRODUCTION[†]

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The investigation of W-pair production offers unique precision tests of the electroweak theory at future e^+e^- colliders, including precise determinations of cross sections, the W-boson mass, and gauge-boson self-couplings. The state-of-the-art and future requirements in the theoretical prediction for the reaction $e^+e^- \rightarrow WW \rightarrow 4f(+\gamma)$ are briefly reviewed.

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The investigation of W-pair production offers unique precision tests of the electroweak theory at future e^+e^- colliders, including precise determinations of cross sections, the W-boson mass, and gauge-boson self-couplings. The state-of-the-art and future requirements in the theoretical prediction for the reaction $e^+e^- \rightarrow WW \rightarrow 4f(+\gamma)$ are briefly reviewed.

1 Introduction

At LEP2, W-pair-mediated four-fermion production was experimentally explored with quite high precision [1]. The total W-pair cross section was measured from threshold up to a centre-of-mass (CM) energy of 209 GeV; combining the cross-section measurements a precision of $\sim 1\%$ was reached. The W-boson mass M_W

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was determined from the threshold cross section with an error of ~ 200 MeV and by reconstructing the W bosons from their decay products within ~ 40 MeV, where a further reduction of the error down to ~ 35 MeV is expected. Deviations from the Standard Model (SM) triple gauge-boson couplings, usually quantified in the parameters Δg_1^Z , $\Delta \kappa_\gamma$, and λ_γ , were constrained within a few per cent. At a future e^+e^- linear collider [2–5], the accuracy of the cross-section measurement will be at the per-mille level, and the precision of the W-mass determination is expected to be 15 MeV by direct reconstruction and about 6 MeV from a threshold scan of the total W-pair-production cross section.

The precision reached at LEP2 triggered considerable theoretical progress in the past years, as it is reviewed in Refs. [6, 7]. In the present calculations, the W bosons are treated as resonances in the full 4-fermion processes, $e^+e^- \rightarrow 4f (+\gamma)$, and radiative corrections (RC) are taken into account in a proper way. The RC can be split into universal and non-universal corrections. The former comprise leading-logarithmic (LL) corrections from initial-state radiation (ISR), higher-order corrections included by using appropriate effective couplings, and the Coulomb singularity. The remaining corrections are called non-universal since they depend on the process under investigation. Since the full $\mathcal{O}(\alpha)$ corrections to the $4f$ processes are not necessary to match the accuracy of LEP2, it is sufficient to take only those corrections into account that are enhanced by two resonant W bosons. The leading term of an expansion about the two W poles provides the so-called double-pole approximation (DPA) [8]. Different versions of such a pole approximation have been used in the literature [9–11]. Although several Monte Carlo programs exist that include universal corrections, only two event generators, YFSWW [11–13] and RACOONWW [10, 14–17], include non-universal corrections. While the DPA approach is sufficient for the LEP2 accuracy [7, 18, 19], the extremely high experimental precision at a future linear collider is a great challenge for future theoretical predictions. Moreover, the DPA is not reliable near the W-pair threshold. In the following, the necessary theoretical improvements will be discussed in some detail.

2 Total Cross Section

The W-pair cross-section measurements at LEP2 have tested the SM predictions at the per-cent level in the energy range between 170 and 209 GeV, thereby rendering non-leading (NL) electroweak corrections of non-universal origin, which are about

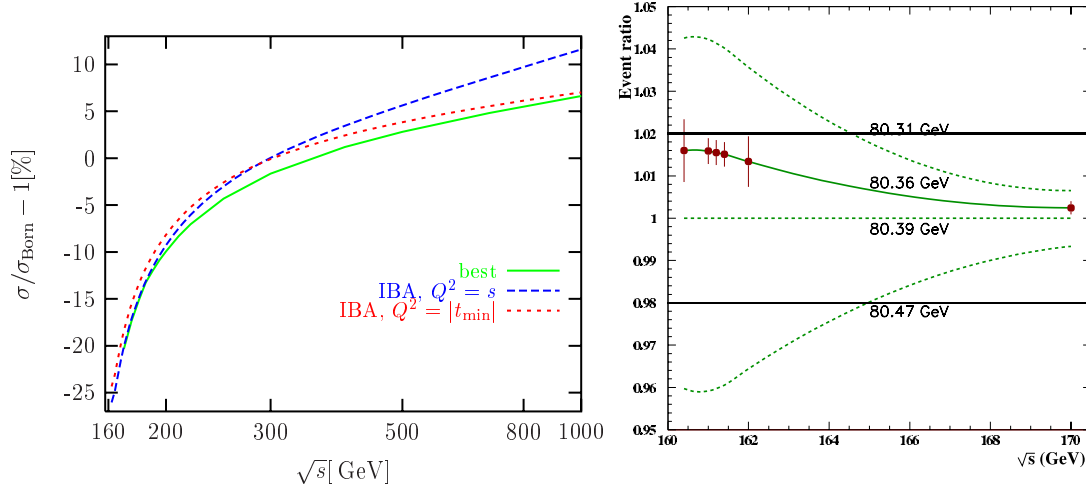


Figure 1: L.h.s.: Relative corrections to the total cross section for the process $e^+e^- \rightarrow u\bar{d}\mu^-\bar{\nu}_\mu$ based on the full DPA of RACOONWW (“best”) and on two IBA versions (taken from Ref. [16]); r.h.s.: Hypothetical data points at a future LC in comparison with cross-section predictions for various values of M_W (taken from Ref. [3]), where the lines at $\pm 2\%$ indicate the TU from neglecting NL corrections.

2%, experimentally significant. The presently available calculations, provided by YFSWW and RACOONWW, which are both based on a DPA, involve a theoretical uncertainty (TU) of about $\sim 0.5\%$ in the range between 170 and 500 GeV [7, 10, 11]. This estimate emerges from a detailed comparison between the two programs and from investigations of intrinsic uncertainties in the DPA versions. The l.h.s. of Figure 1 compares the full DPA RC with two improved Born approximations (IBA) that are based on universal corrections only, which illustrates that non-universal RC become more and more important at higher energies. Measurements at future LCs, which will be precise within a few per mille, require a TU of 0.1% or better. In order to illustrate the consequences of this requirement on theoretical predictions, in Table 1 we collect some estimates of corrections that are neglected in present calculations. The table shows that there is a variety of neglected terms potentially of the order of 0.1%, and that an improvement on the TU to this level requires a full $\mathcal{O}(\alpha)$ calculation of the processes $e^+e^- \rightarrow 4f$ and a proper inclusion of the most important two-loop effects. While the virtual one-loop RC to $e^+e^- \rightarrow 4f$ are not known yet, the real $\mathcal{O}(\alpha)$ RC, which are induced by the processes $e^+e^- \rightarrow 4f + \gamma$, are available [14, 20]. However, at $\mathcal{O}(\alpha^2)$, real photonic corrections beyond the LL

Neglected effect	Estimate for relative numerical impact
RC to background diagrams	$(\alpha/\pi) \times (\Gamma_W/M_W) \times \text{const} \sim 0.1\%$
Scale in coupling of NL RC	$(\Delta\alpha/\alpha) \times \text{NL} \sim 6\% \times 2\% \sim 0.1\%$
Squared NL corrections	$(\text{NL})^2 \sim 0.04\%$
Interference of NL and ISR	$\text{NL} \times \text{ISR} \sim 2\% \times (\alpha/\pi) \ln(s/m_e^2) \sim 0.1\%$

Table 1: Estimates of some presently missing RC to the total W-pair cross section at $\sqrt{s} \sim 200$ GeV

approximation and the effects of collinear emission of $f\bar{f}$ pairs must be included.

The necessity of the full treatment of $e^+e^- \rightarrow 4f$ at one loop becomes even more obvious near the W-pair threshold ($\sqrt{s} \lesssim 170$ GeV) where the TU of the DPA approach runs out of control because of the increasing relative importance of the non-resonant contribution. Therefore, at LEP2 an IBA was confronted with the cross section measured at $\sqrt{s} = 161$ GeV, since the experimental error of 12% was much larger than the IBA uncertainty of about 2%. The r.h.s. of Figure 1 shows the possible result of a threshold scan at a future LC running with high luminosity and the sensitivity of the cross section to the W-boson mass. Without reducing the TU to the level of a few 0.1% the aimed precision of 6 MeV in the M_W determination will be impossible.

At high scattering energies, $\sqrt{s} \gg M_W$, (and fixed angles) the RC are dominated by electroweak logarithms of the form $[\alpha \ln^2(s/M_W^2)]^n$, known as Sudakov logarithms, and single logarithms like $[\alpha \ln(s/M_W^2)]^n$. While these terms are implicitly contained in the present DPA approaches at the one-loop level, the higher-order logarithms, $n \geq 2$, are not yet included in existing generators. These missing terms are potentially numerically relevant for $\sqrt{s} \gtrsim 500$ GeV. The existing efforts in the calculation of these logarithms in virtual corrections are reviewed in Ref. [21]. In addition also the corresponding logarithms from real corrections and enhanced logarithms resulting from small scattering angles (Regge limit) have to be investigated.

3 Invariant-Mass Distributions and W-Boson Mass

The invariant-mass distributions of the W bosons are the central observables in the M_W determination from the direct reconstruction of the W bosons from their decay products. While the overall scale of the distributions more or less reflects the situ-

ation of the total cross section, the shapes and peak positions of the Breit–Wigner-type resonances are sensitive to M_W . Based on a comparison between YFSWW and RACOONWW, the present TU induced by missing RC was estimated to $\lesssim 1\%$ in the invariant-mass distributions [7] and to ~ 5 MeV in the reconstructed W-boson mass [18], which is small compared to the aimed precision of 35 MeV at LEP2. Note that the TU is also smaller than the expected accuracy of 15 MeV at a LC, but a further reduction of the TU would certainly be welcome. This improvement would, however, also require a much better understanding of QCD corrections that are connected with the W decays and a proper matching between parton-level calculations and hadronization procedures.

4 Angular Distributions and Anomalous Couplings

A proper way to study possible deviations from the SM triple gauge-boson couplings is the analysis of angular distributions, where the W-production angle plays the most important role. In Figure 2 we compare the influence of anomalous charged triple gauge-boson couplings with the effect of the non-universal corrections for the process $e^+e^- \rightarrow u\bar{d}\mu^-\bar{\nu}_\mu$ at the CM energy of $\sqrt{s} = 200$ GeV. Following a convention widely used in the LEP2 data analysis, we consider only the coupling constants g_1^Z , κ_γ , and λ_γ , where Δ indicates the deviation from the SM values $g_1^Z = \kappa_\gamma = 1$ and $\lambda_\gamma = 0$. In the figures all numbers are normalized to the tree-level cross section including higher-order LL ISR. The relative deviations for different values of the anomalous couplings are compared with the predictions including non-universal $\mathcal{O}(\alpha)$ corrections instead of anomalous couplings. The labels indicate the values of the corresponding anomalous coupling constants, which are chosen to be of the order of the actual accuracy achieved by the LEP experiments, i.e. of the order of a few per cent. The comparison shows clearly that the non-universal corrections are of the same size as the possible contributions from anomalous couplings and, thus, had to be taken into account in the determination of limits on anomalous couplings at LEP2. The angular distributions obtained with YFSWW and RACOONWW differ by about $\lesssim 1\%$ [7]. A detailed analysis [19] showed that this TU, for instance, leads to an error of 5×10^{-3} in the parameter λ_γ , which is sufficient for LEP2. At a future LC, however, the sensitivity to the parameters g_1^Z , κ_γ , and λ_γ will be of the order of 10^{-3} , so that drastic improvements in the predictions are necessary in order to match this precision. Again the inclusion of the full $\mathcal{O}(\alpha)$ corrections to $e^+e^- \rightarrow 4f$ and improvements by higher-order corrections are indispensable.

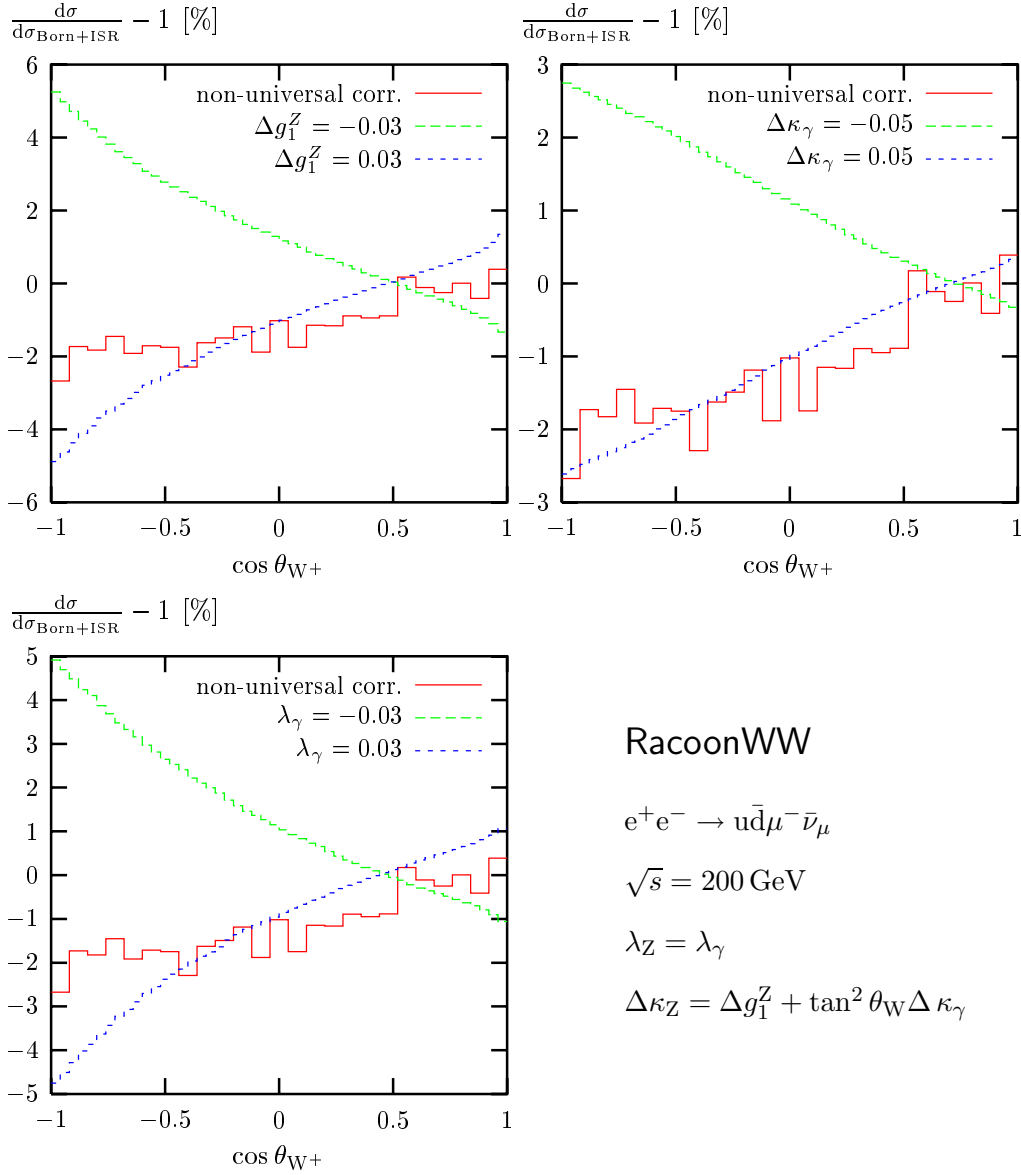


Figure 2: Influence of anomalous triple gauge-boson couplings and non-universal corrections in the W^+ -production-angle distribution (taken from Ref. [22])

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